

## PATENT COOPERATION TREATY

PCT

## NOTIFICATION OF ELECTION

(PCT Rule 61.2)

From the INTERNATIONAL BUREAU

To:

Assistant Commissioner for Patents  
United States Patent and Trademark  
Office  
Box PCT  
Washington, D.C.20231  
ETATS-UNIS D'AMERIQUE

in its capacity as elected Office

Date of mailing (day/month/year) 07 April 2000 (07.04.00)	
International application No. PCT/US99/19601	Applicant's or agent's file reference 4463PCT
International filing date (day/month/year) 25 August 1999 (25.08.99)	Priority date (day/month/year) 26 August 1998 (26.08.98)
Applicant EULER, William, B. et al	

1. The designated Office is hereby notified of its election made:

☒ in the demand filed with the International Preliminary Examining Authority on:23 February 2000 (23.02.00)☐ in a notice effecting later election filed with the International Bureau on:2. The election ☒ was  
☐ was not

made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer F. Baechler
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# PATENT COOPERATION TREATY

## PCT

### INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

7  
2000 27 AUG 2000

Applicant's or agent's file reference 4463PCT	FOR FURTHER ACTION See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)	
International application No. PCT/US99/19601	International filing date (day/month/year) 25 AUGUST 1999	Priority date (day/month/year) 26 AUGUST 1998
International Patent Classification (IPC) or national classification and IPC IPC(7): G01B 09/02 and US Cl.: 356/357		
Applicant THE BOARD OF GOVERNORS FOR HIGHER EDUCATION, STATE OF RHODE ISLAND AND PROVIDENCE PLANTATIONS		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.
2. This REPORT consists of a total of 3 sheets.  
☐ This report is also accompanied by ANNEXES, i.e., sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority. (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

These annexes consist of a total of 0 sheets.

3. This report contains indications relating to the following items:

- I ☒ Basis of the report
- II ☐ Priority
- III ☐ Non-establishment of report with regard to novelty, inventive step or industrial applicability
- IV ☐ Lack of unity of invention
- V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- VI ☐ Certain documents cited
- VII ☐ Certain defects in the international application
- VIII ☐ Certain observations on the international application

Date of submission of the demand  23 FEBRUARY 2000	Date of completion of this report  25 MARCH 2000
Name and mailing address of the IPEA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231  Facsimile No. (703) 305-3230	Authorized officer f ROBERT KIM Telephone No. (703) 308-0956

## INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US99/19601

**I. Basis of the report**1. With regard to the **elements** of the international application:\*☒ the international application as originally filed☒ the description:

pages 1-6 , as originally filed  
pages NONE , filed with the demand  
pages NONE , filed with the letter of \_\_\_\_\_

☒ the claims:

pages 1-16 , as originally filed  
pages NONE , as amended (together with any statement) under Article 19  
pages NONE , filed with the demand  
pages NONE , filed with the letter of \_\_\_\_\_

☒ the drawings:

pages 1-5 , as originally filed  
pages NONE , filed with the demand  
pages NONE , filed with the letter of \_\_\_\_\_

☒ the sequence listing part of the description:

pages NONE , as originally filed  
pages NONE , filed with the demand  
pages NONE , filed with the letter of \_\_\_\_\_

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

These elements were available or furnished to this Authority in the following language \_\_\_\_\_ which is:

☐ the language of a translation furnished for the purposes of international search (under Rule 23.1(b)).☐ the language of publication of the international application (under Rule 48.3(b)).☐ the language of the translation furnished for the purposes of international preliminary examination (under Rules 55.2 and/or 55.3).3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:☐ contained in the international application in printed form.☐ filed together with the international application in computer readable form.☐ furnished subsequently to this Authority in written form:☐ furnished subsequently to this Authority in computer readable form.☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.4. ☒ The amendments have resulted in the cancellation of:☒ the description, pages NONE☒ the claims, Nos. NONE☒ the drawings, sheets/fig NONE5. ☐ This report has been drawn as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).\*\*

\* Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17).

\*\*Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.

## INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US99/19601

**V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

## 1. statement

Novelty (N)

Claims 1-16 YESClaims none NO

Inventive Step (IS)

Claims 1-16 YESClaims none NO

Industrial Applicability (IA)

Claims 1-16 YESClaims none NO

## 2. citations and explanations (Rule 70.7)

Claims 1-16 meet the criteria set out in PCT Article 33(2)-(4), because the prior art does not teach or fairly suggest an interferometric strain sensor wherein the sensor having a gage factor of least 100 when the strain is applied to the sensor in which the sensor is a passive sensor with one of the layers being filled with particulate.

----- NEW CITATIONS -----

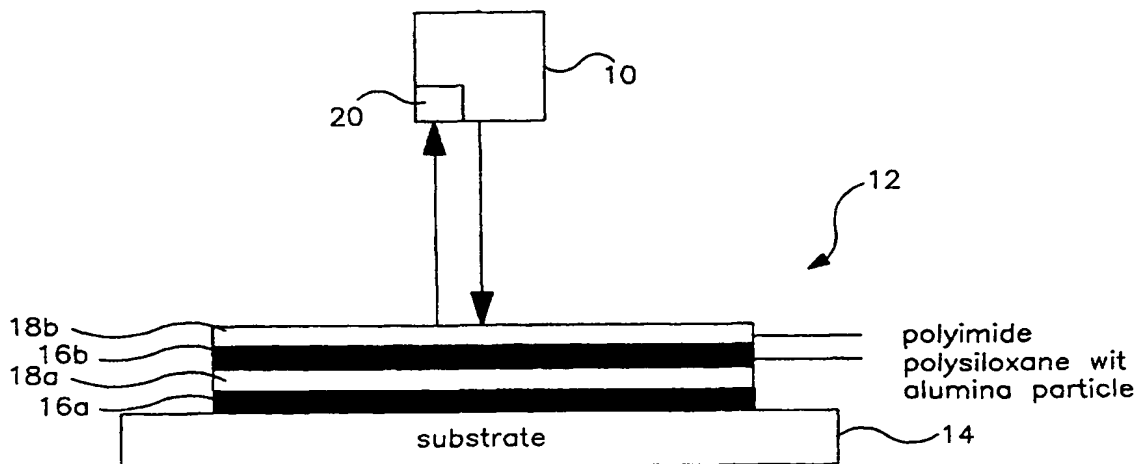
NONE



## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<b>(51) International Patent Classification <sup>6</sup> :</b>  <b>G01B 9/02</b>	<b>A1</b>	<b>(11) International Publication Number:</b> <b>WO 00/12960</b>  <b>(43) International Publication Date:</b> 9 March 2000 (09.03.00)
<b>(21) International Application Number:</b> PCT/US99/19601 <b>(22) International Filing Date:</b> 25 August 1999 (25.08.99) <b>(30) Priority Data:</b> 60/097,989 26 August 1998 (26.08.98) US <b>(71) Applicant (for all designated States except US):</b> THE BOARD OF GOVERNORS FOR HIGHER EDUCATION, STATE OF RHODE ISLAND AND PROVIDENCE PLANTATIONS [US/US]; 199 Promenade Street, Providence, RI 02908 (US). <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> EULER, William, B. [US/US]; 35 Flintstone Road, Narragansett, RI 02882 (US). GREGORY, Otto, J. [US/US]; 87 Westwind Road, Wakefield, RI 02879 (US). HUSTON, Gregg, C. [US/US]; 29 Tomahawk Trail, Wakefield, RI 02879 (US). <b>(74) Agents:</b> STEVENS, Richard, L. et al.; Samuels, Gauthier & Stevens, Suite 3300, 225 Franklin Street, Boston, MA 02110 (US).		<b>(81) Designated States:</b> AU, CA, CN, JP, KR, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).  <b>Published</b> <i>With international search report.</i>

**(54) Title:** THIN FILM STRAIN SENSORS BASED ON INTERFEROMETRIC OPTICAL MEASUREMENTS

**(57) Abstract**

The invention relates to polymeric/semiconductor thin film strain gauges comprising visible light from spectrometer (10) which is directed onto a thin film passive sensor (12) having a transparent glass substrate (14) and a laminated construction in succession from the substrate (14), of a polyimide layer (18a), a polysiloxane layer (16a) filled with alumina particles, a polyimide layer (18b) and a polysiloxane layer (16b) filled with alumina particles.

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Title

Thin Film Strain Sensors Based on Interferometric Optical Measurements

Background of the Invention1. Field of the Invention

5 The invention relates to polymeric/semiconductor thin film strain gauges

2. Description of the Relevant Art

Many civil engineering structures display fatigue, and occasionally failure, after years of exposure to natural forces. In other instances, the failure is a result of a catastrophic event, such as an earthquake, tornado, or hurricane. There is a need for  
10 an inexpensive, robust, and sensitive strain gage that is unaffected by seasonal environmental variations. Further, such a sensor should be simple, easily installed, and readily integrated into modern data communication systems.

The sensor system disclosed herein can monitor the integrity of structures for the purpose of public safety and maintenance. Specific applications include building,  
15 road, and bridge integrity. The system employs, as the sensing component, multiple optical strain gages that are inexpensive, inert to natural environments, and physically robust. Combined with an automated data collection and diagnostic analysis programming, such sensors and their optical fiber data links can be placed on the superstructures and footings of bridges, in the support components of buildings, or  
20 embedded into the surfaces of roads and pedestrian skywalks. The 'health' of such structures and surfaces can be automatically monitored and assessed with a minimum of human time allocation. Detailed use information would also be valuable in assessing the need for routine maintenance or for the need for repair after a potential catastrophic loading.

25 Summary of the Invention

The sensitivity and the passivity behavior of the sensors distinguishes from the prior art. Current resistive strain sensors have gage factors (the measure of sensitivity) of about 2-3. The disclosed sensors have gage factors on the order of 200-800. It is not believed the prior art discloses any passive sensors that have a memory that does

not rely on a power source.

Thin films of semiconductors or polymers are used to measure strain. The thin films are layered with each layer consisting of materials with different refractive indices. Because each layer has a different refractive index, light that is introduced into the composite structure can either be reflected or pass through at each interface. This allows interference of the incident light that passes through with light that is reflected resulting in a measurable absorption change. The degree of interference is sensitive to the refractive index and thickness of each layer. The thickness of the each layer changes with application of an external stress. The consequence of this is that the light absorption changes as a function of strain so that the absorption change can be used to measure the strain.

There are two types of interferometric sensors disclosed herein, active and passive. An active sensor responds to the strain reversibly, i.e. as the strain changes the absorption changes in a reversible and predictable fashion. This type of sensor is used to measure the existing strain on a structure.

A passive sensor has a memory of the maximum strain experienced by the structure. For example, if a structure experiences a large deformation ( a large strain) but then relaxes to a small rest value, the large deformation is not reversible. An active sensor will measure the strain events only if continuously monitored while the passive sensor will measure only the maximum strain experienced. If the active sensor is not being monitored while the maximum strain is occurring, the large strain excursion will not be observed. The passive sensor overcomes this problem.

Broadly the invention comprises both active and passive sensors which preferably are used in the same structure. Both sensors are constructed by layering materials, either semiconductors or polymers having different refractive indices. The sensitivity is increased when the difference in refractive index is maximized and also as the number of layers is increased. The passive sensors are constructed by adding small particulates to one set of layers.

#### Brief Description of the Drawings

Fig. 1 is an illustration of a passive sensor;

Figs. 2a and 2b are illustrations of an alternative embodiment of Fig. 1;



Fig. 3 is a graph of the optical response of an active sensor;

Fig. 4 is a graph of the optical response of an passive sensor; and

Fig. 5 is a graph of the optical response of a passive sensor;

#### Description of the Preferred Embodiment(s)

5 Incident light can be measured in reflectance or transmission to determine the strain.

Referring to Fig. 1, reflectance mode, visible light from a spectrometer 10, such as Perkin Elmer Lambda 2, is directed onto a thin film passive sensor shown generally at 12. The sensor 12 comprises a transparent glass substrate 14 and a  
10 laminated construction in succession from the substrate 14, of a polyimide layer 18a, a polysiloxane layer 16a filled with alumina particles, a polyimide layer 18b and a polysiloxane layer 16b filled with alumina particles. The incident light beam is normal to the sensor surface. The light is collected along the incidence beam path in a photomultiplier tube detector 20 in the spectrometer 10. The layers can range in  
15 thickness from 1-20 microns. The passive sensor is prepared by mixing 50 nm particles of aluminum oxide in with the polysiloxane layer in an amount of 0.5 to 10% by weight based on the total weight of the polysiloxane layer. During preparation, the small particles aggregate to some (currently unknown) degree. Under strain, some of the particles in the aggregate separate and the polymer fills in between the newly  
20 separated alumina particles. When the strain is removed, the particles cannot reaggregate because of the intervening polymer. This is detected optically because the size of the aggregates determines the amount of light scattered off of the sample: as the aggregate size changes because of the strain, the amount of light directed toward the detector changes since the detector only samples a small volume of space. The passive  
25 sensor requires no power to achieve its memory effect.

Referring to Fig. 2a, the transmission mode, for an active sensor a capillary tube 30, e.g. i.d. 0.5 mm; o.d 0.7 mm, is used as a light conduit. Thin films 32, e.g. polysiloxane/polyimide, are deposited onto the outside walls of the capillary tube 30 and then these films are coated with aluminum 34. The aluminum 34 serves as a  
30 mirror to keep all the light confined in the tube 30 and to protect the entire structure from the surrounding environment. A fiber optic source 36 inputs light in a

wavelength range of 500 to 1,000 Angstroms into one end of the capillary tube 30 parallel to the longitudinal axis of the tube and a detector 38 collects the light at the other end.

In the capillary configuration, the tube 30 acts as both a waveguide and a  
5 sensor. Under no strain, most of the light passes down the tube without interacting with the walls. With application of a strain the capillary tube 30 bends, Fig. 2b, so that a significant amount of light is introduced into the thin film coatings along the tube walls. Two effects cause a modulation of the output light intensity. First, the path length is changed so any absorption that occurs is increased, depending upon the  
10 absorptivity of the wall materials and the number of bounces the light undergoes. Second, the interference effect observed as light passes through the thin film layers still is operative, also causing intensity modulation by constructive or destructive interference, depending on the refractive index and thickness of each layer and the wavelength of light used.

15 The film thicknesses 32 are on the order of 1 to 20 microns, thinner being a bit better. The wavelengths of maximum response depends upon the layer thicknesses, but that wavelength can be chosen arbitrarily to match the thin film structure. The aluminum coating has a thickness of between 400 to 800 nm.

The alternating layers must have a different refractive index and the larger the  
20 difference, the better the sensor response. Polyimide has  $n = 1.6-1.7$  (depending upon the exact polyimide used, the nature of the curing, and the supplier); polysiloxane has  $n=1.44$ . Other commonly available transparent polymers polyethylene, polypropylene, Teflon®, polyvinylidene fluoride, polyester, etc. have refractive indices around 1.4 and could substitute for the polysiloxane layer. High refractive index  
25 polymers such as polycarbonates have refractive indices approximately the same as polyimide.

A preferred sensor system requires both a passive and an active sensor in close proximity. The passive sensor measures the maximum strain excursion experienced but not a temporal history, i.e. the measured strain may be current or previous. Thus,  
30 the role of the active sensor is to measure the existing strain at the time of measurement.

The sensors can be applied to a structure by currently known bonding techniques used for the current generation of strain sensors. Because the sensors are small, they will measure the strain of the substrate material reliably. The optical source and detector need not be embedded with the sensor. With the appropriate fiber optic connections, the optical measurement can be made periodically by connecting a handheld spectrometer to the input and output of the sensor. Thus, for example, after an earthquake the maximum strain experienced by each structural element in a building could be determined well after the event (days or weeks) to establish the safety of the building since the passive sensor retains this information even with (the likely) loss of power. Alternatively, a fiber optic network connected to each sensor in a building that remotely senses the strain automatically. However, during a catastrophic event the fiber network is likely to break and prevent this mode of operation.

The materials used in the sensor are both inexpensive and robust. For example, the polysiloxane is a commercially available gasket sealer. The capillary configuration is especially attractive for long term applications because, if necessary, the entire sensor can be enclosed. Then, for example, if the sensor is to be used in a harsh environment such as a bridge, the entire sensor can be isolated from wind, rain, salt spray, etc. because any coatings applied outside of the aluminum layer have no affect on the sensor performance.

20

### Examples

Examples of the sensor response are given in Figures 3, 4 and 5. The light source was a tungsten lamp, and strain was applied by four point bending, see ASTM C-1341-97.

Figure 3 shows the response of two different active strain sensors, one with 12 layers (6 alternating layers of polysiloxane and polyimide) and one with 26 alternating layers. Layer thickness was about 10 microns. The absorbance was monitored at 600 nm as a function of applied strain with the results shown. The gage factor is a function of the number of layers indicating the interferometric nature of the response. Further, the gage factors are large, more than two orders of magnitude larger than found in typical resistance strain gages. Finally, the response is linear and reversible over the entire range up to about 2000  $\mu$ strain (this is the typical limit required for structural

applications since most materials exceed their plastic deformation limits at about 2000  $\mu$ strain).

Figure 4 shows the response of a passive strain gage having 26 alternating layers. The layer thickness was about 10 microns. As strain is applied, the response is similar to an active gage. The absorbance was monitored at 600 nm. However, when the strain is released the response is no longer reversible, i.e., the 0-strain absorbance depends upon the history of the sample. This is demonstrated in Figure 4 for several different strain excursions. The virgin gage has an absorbance value at 600 nm of  $A = 0.73$ . Application of 300  $\mu$ strain changes this to  $A = 0.83$ . Upon release of the stress back to 0  $\mu$ strain the absorbance returns to  $A = 0.78$ , shown as the short dashed line in Figure 4. Application of any strain less than 300  $\mu$ strain follows the dashed line path reversibly. However, if the strain exceeds 300  $\mu$ strain, then the path reverts to the solid line as shown for the 600  $\mu$ strain point in Figure 4. Now when the stress is released, a new path is taken, shown as the dotted line, and to a new absorbance at 0  $\mu$ strain.

The increments between successive strain excursions decreases with increasing strain (i.e., the passive response is nonlinear) and this is demonstrated in Figure 5. The 12 layer gage has a small gage factor but a larger, nearly linear response range. The 26 layer gage has a larger gage factor but becomes clearly nonlinear at significantly smaller maximum strains.

The foregoing description has been limited to a specific embodiment of the invention. It will be apparent, however, that variations and modifications can be made to the invention, with the attainment of some or all of the advantages of the invention. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the invention.

Having described our invention what we now claim is:

1        1. An interferometric strain gage sensor which comprises:  
2        a support;  
3        a first layer of polymeric material having a first refractive index;  
4        a second layer of polymeric material having a second refractive index which  
5 second refractive index is distinct from the first refractive index, the sensor having a  
6 gage factor of at least 100 and light energy communicates with the sensor, when a  
7 strain is applied to the sensor, the light energy is partly absorbed and the change in  
8 light energy correlates to the strain applied.

1        2. The sensor of claim 1 which comprises:  
2        a plurality of alternating first and second layers.

1        3. The sensor of claim 2 wherein the first layer has a refractive index of  
2 approximately 1.6 to 1.7 and is selected from the group consisting of polyimides and  
3 polycarbonates.

1        4. The sensor of claim 3 wherein the first layer is polyimide.

1        5. The sensor of claim 2 wherein the second layer has a refractive index of  
2 about 1.4 and is selected from the group consisting of polysiloxane, polyethylene,  
3 polypropylene, Teflon®, polyvinylidene fluoride and polyester.

1        6. The sensor of claim 5 wherein the second layer is polysiloxane.

1        7. The sensor of claims 4 or 6 wherein the thicknesses of the layers are  
2 between about 1 to 20 microns.

1        8. The sensor of claim 1 which comprises:  
2 means for contacting the sensor with light energy; and  
3 means for measuring changes in the light energy.

1        9. The sensor of claim 1 wherein the sensor is a passive sensor and one of  
2 said layers is filled with particulate.

1           10. The sensor of claim 9 wherein there are multiple first and second layers in  
2 alternating relationship, the first layer selected from the group consisting of polyimides  
3 and polycarbonates, the second layer selected from the group consisting of  
4 polysiloxane, polyethylene, polypropylene, Teflon®, polyvinylidene fluoride and  
5 polyester.

1           11. The sensor of claim 10 wherein the first layer is polyimide and the  
2 second layer is polysiloxane filled with aluminum oxide particulate.

1           12. The sensor of claim 9 which comprises:  
2 means for contacting the sensor with light energy; and  
3 means for measuring changes in the light energy.

1           13. The sensor of claim 1 wherein the sensor is an active strain gage and  
2 comprises a tube-like support for the first and second layers.

1           14. The sensor of claim 13 wherein the first layer has a refractive index of  
2 approximately 1.6 to 1.7 and is selected from the group consisting of polyimides and  
3 polycarbonates, and wherein the second layer has a refractive index of about 1.4 and is  
4 selected from the group consisting of polysiloxane, polyethylene, polypropylene,  
5 Teflon®, polyvinylidene fluoride and polyester.

1           15. The sensor of claim 14 wherein the outer most layer is coated with  
2 aluminum.

1           16. The sensor of claim 15 which comprises:  
2 means for contacting the sensor with light energy; and  
3 means for measuring changes in the light energy.

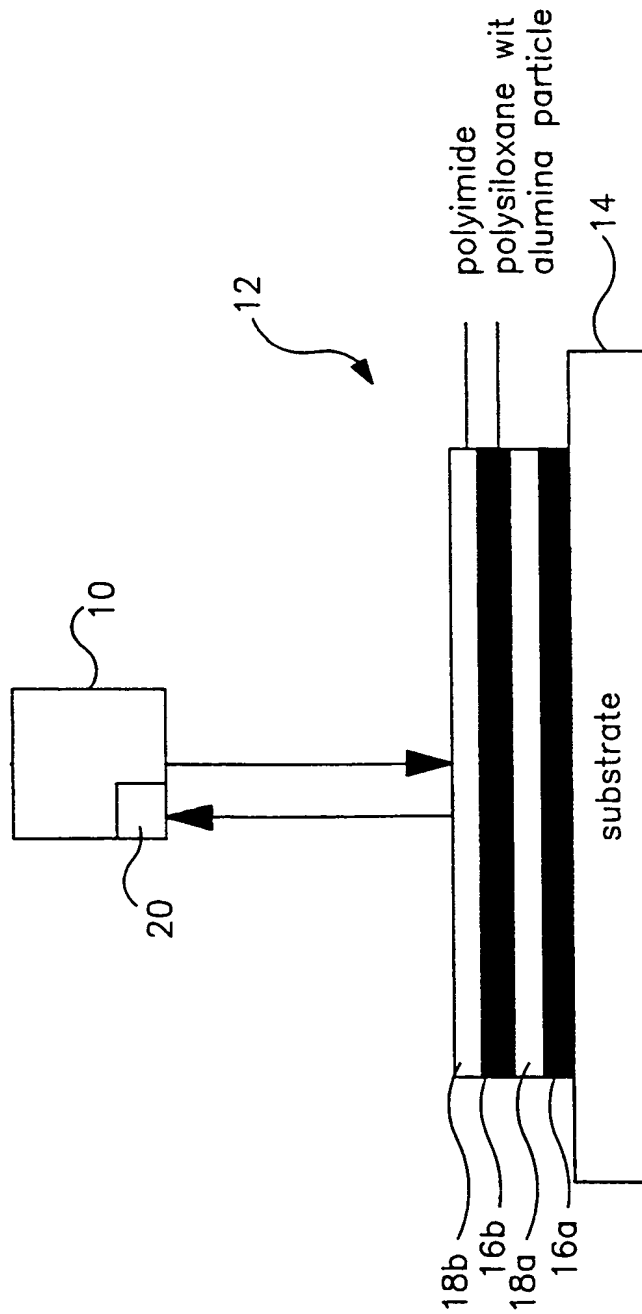


FIG. 1

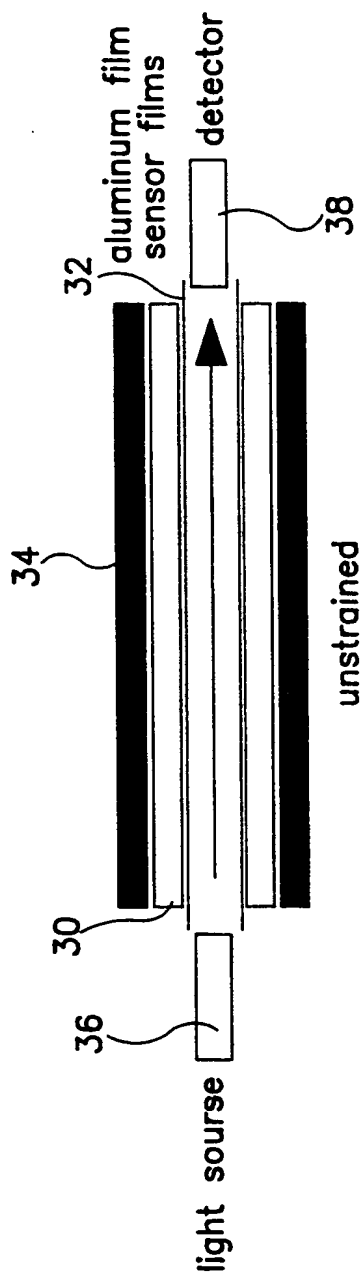


FIG. 2a

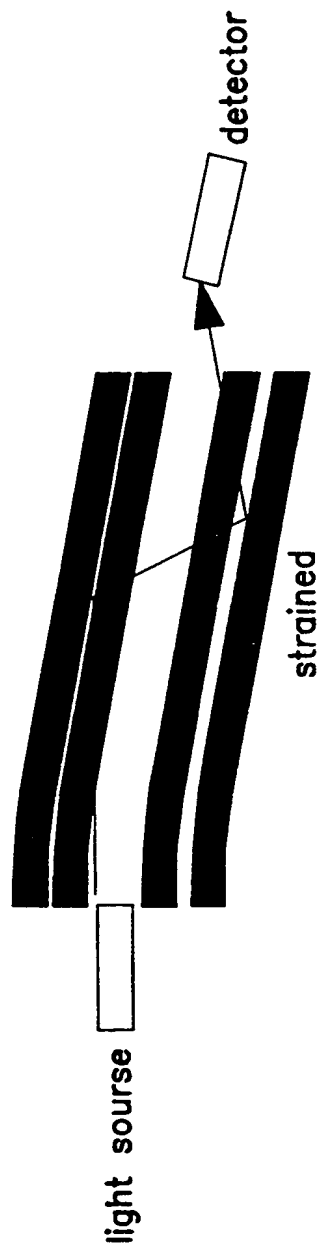


FIG. 2b



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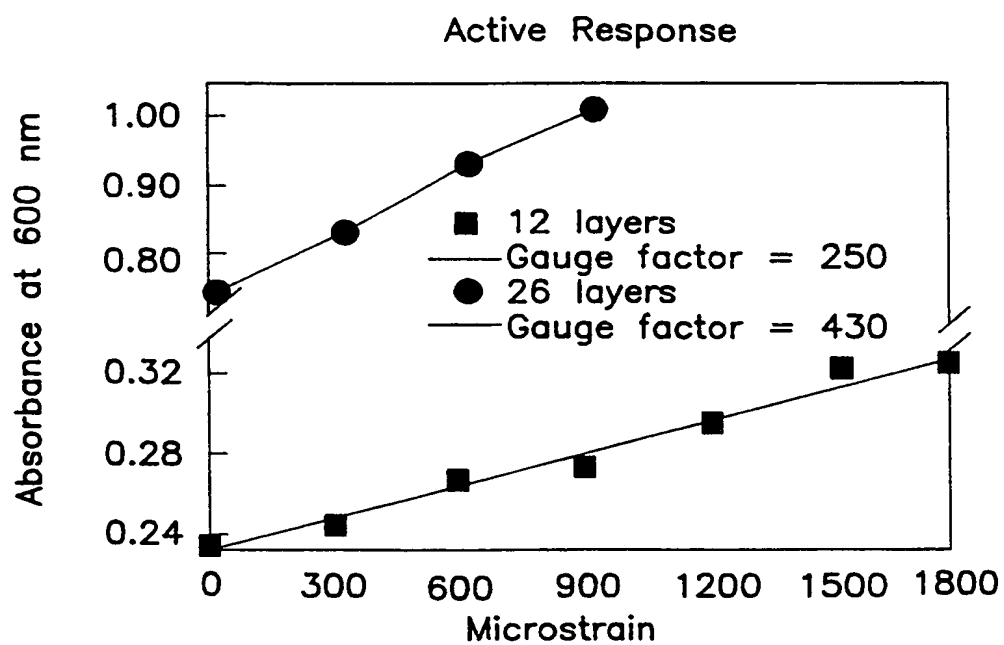


FIG. 3

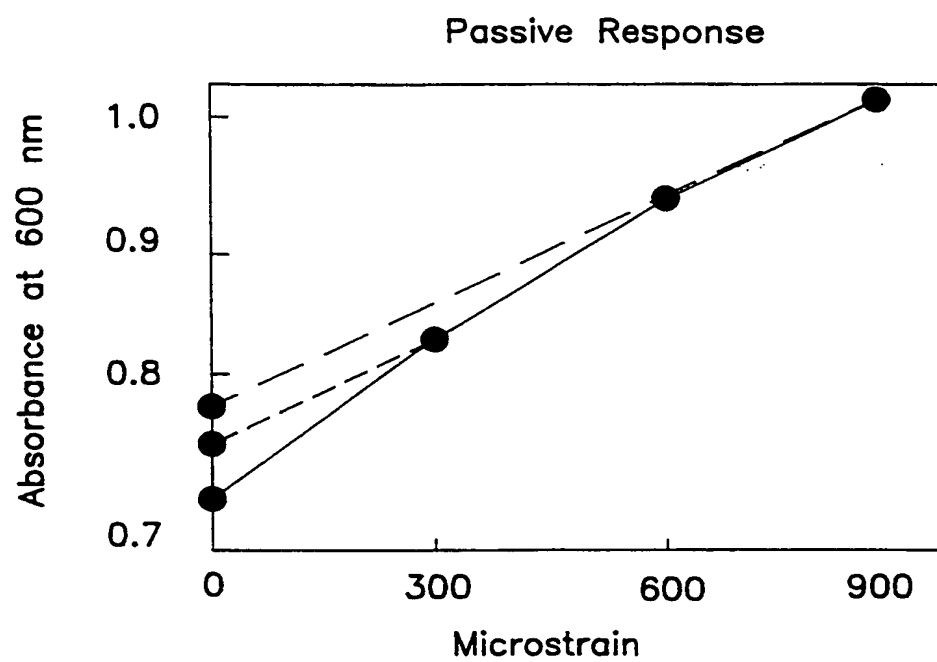


FIG. 4

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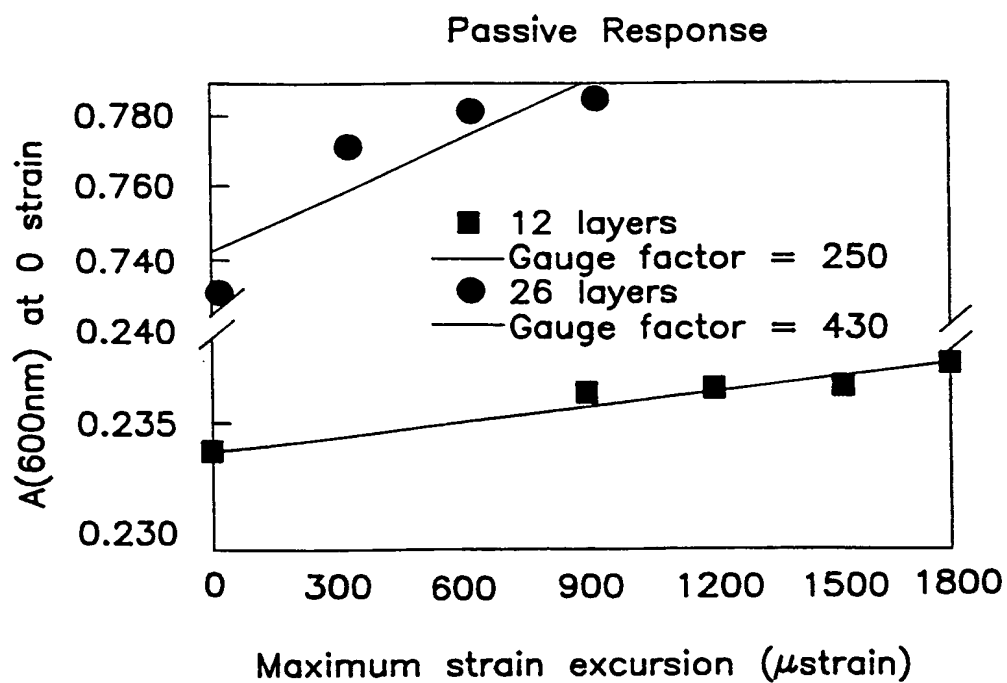


FIG. 5

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US99/19601

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G01B 09/02

US CL : 356/357

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/357, 359, 360

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

US PTO APS: thickness, interference, polyfilm

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,120,966 A (KONDO) 9 JUNE 1992 (09.06.92), see entire document	1-16

☐

Further documents are listed in the continuation of Box C.

☐

See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
*A* document defining the general state of the art which is not considered to be of particular relevance	*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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Date of the actual completion of the international search

30 SEPTEMBER 1999

Date of mailing of the international search report

18 OCT 1999

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